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AEROELASTIC EFFECTS OF AERODYNAMIC HEATING

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Introduction

In much of the discussion of the effects of aerodynamic heating, attention has been focused on the reduction of the strength of materials as the temperature increases and on the probability of local melting when the skin temperature reaches the melting temperature. We now realize that long before a skin temperature is reached at which these effects occur, aerodynamic heating will give rise to serious structural problems.

One of the early experiments conducted by the NACA was designed to check the temperature distribution through the structure at various times during and following a rapid acceleration of airflow to Mach Number 2. An aluminum alloy wing specimen of multiweb construction was placed at zero angle of attack in an airstream having a stagnation temperature of 500°F and sea level static pressure. The unexpected result can best be shown by a short motion picture.

The first part of the motion picture shows the entire test, and was taken at five times the speed of projection. The flow is from left to right and the oscillations observed are produced by the starting shock wave. As soon as steady flow at Mach Number 2 is established, the oscillations disappear and the wing comes to rest. The wing is being subjected to aerodynamic heating by the air stream but at first shows no sign of distress. The first indication of trouble appears at the upper right-hand corner.

The second part of the picture shows a high-speed shot taken at 25 times projection speed. This shows clearly the chordwise "flag waving" type of flutter that preceded failure of the wing.

In order to be sure that the catastrophic flutter undergone by the specimen in this first test was indeed precipitated by aerodynamic heating, the test was repeated in a jet of the same Mach number, but having a stagnation temperature of only 100°F; in this test no flutter was observed and the model remained entirely unharmed.

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From this and other experiments and theoretical analyses it seems clear that an important effect of aerodynamic heating is an interaction between the heating, the structural stiffness, and the air forces. It is well known that during the last decade aeroelasticity has assumed a major role in the design of high-speed aircraft. Increased flight speeds have raised the magnitudes of the aerodynamic forces available for the excitation of aeroelastic phenomena; on the other hand, the provision of adequate structural stiffness to prevent undesirable aeroelastic behavior has been subject to the limitations inherent in the thin wing profiles and slender bodies needed for high-speed flight. In addition to the more familiar static and dynamic aeroelastic problems, such as aileron reversal and bending-torsion flutter, new types of aeroelastic phenomena have arisen. The introduction of low aspect ratio planforms, as in delta wings, has been accompanied by the possibility of aeroelastic behavior associated with chordwise distortions. Also, local flutter of thin skin panels has been recognized as a potential threat, particularly at supersonic speeds.

All of these aeroelastic phenomena are modified by aerodynamic heating, to the first order by the effects of the heating on the structural and aerodynamic parameters, but we cannot ignore the possibility under severe conditions of coupling between the resultant structural deformations and the heating. This paper is concerned primarily with the first order effects on the structural parameters.

Effects of Aerodynamic Heating on Structural Stiffness

In all aeroelastic problems there is an interaction between aerodynamic and elastic forces — the aerodynamic forces tending to distort the structure, while the elastic forces tend to resist distortion. In addition, inertial and damping forces are involved in dynamic aeroelasticity. The principal first order influence of aerodynamic heating in aeroelasticity is presumed to reside in its effect on the elastic forces that enter into the aeroelastic force balance. A reduction in the magnitude of the elastic forces available to resist distortion — or, in other words, a reduction in structural stiffness — could lead to increased susceptibility to aeroelastic difficulties. We must seek, therefore, to discover the ways in which the effective stiffnesses of aircraft structural components can be affected by aerodynamic heating and thence to examine the extent to which the altered stiffnesses might influence aeroelastic behavior.

Reduced elastic moduli.—The first, and most obvious, consideration that presents itself is that of the effect of elevated temperatures on the elastic moduli of aircraft structural materials. In Figure 1 are shown the variations with temperature of the moduli of elasticity of four materials that may find application in various elevated temperature ranges — an aluminum alloy (7075-T6), titanium alloy (RC130B), a stainless steel (Stainless W), and Inconel X. For reference, an auxiliary abscissa is given, indicating the Mach numbers at which the corresponding temperatures could be attained through aerodynamic heating during sustained flight in the stratosphere. As can be seen, the elastic modulus of each material exhibits a drop with increasing temperatures. Although such decreases in structural stiffness influence all aeroelastic phenomena, they nevertheless present no great problem to the aeroelastician; his aeroelastic analyses must simply be based on the value of elastic modulus appropriate to the temperature of concern.

Local buckling and panel flutter.— But the losses in stiffness due to change in elastic modulus are associated with only one consequence of aerodynamic heating, namely, a simple rise in temperature. Of generally greater significance are the losses in effective stiffness that result from transient thermal gradients in the aircraft structures, and the thermal stresses they produce. Figure 2 shows in a qualitative fashion the temperatures and stresses that might develop with time in a multiweb wing as a result of accelerated flight to supersonic speeds. The upper chart shows plots of temperature versus time for a point "A" on the cover of the wing and for a point "B" on the web in the interior of the structure. The interior temperature may lag substantially behind the temperature of the outer skin which is being heated directly by heat transfer from the boundary layer. Eventually, if flight at a given Mach number is sustained, all points in both the web and the covers would reach essentially the same temperature; but in the transient range shown here the differences in temperature between webs and cover give rise to thermal stresses in the spanwise direction. As shown by the lower chart of thermal stress against time, compressive stress develops in the covers while tensile stress is produced in the webs. These stresses arise simply as a result of the fact that the heated covers wish to expand longitudinally but tend to be constrained from doing so by the relatively cool webs; since the thermal stresses must, of necessity, be self equilibrating, there is no net thrust over the cross section.

It is entirely possible for the compressive stresses in the cover to buckle the cover skin between webs if the stresses become sufficiently high, and this possibility is of significance in connection with local panel flutter in supersonic flight. Theoretical studies have indicated that a buckled panel is more susceptible to panel flutter than a non-buckled panel, as is shown in Figure 3.

This figure shows theoretical estimates of the thickness to length ratio required to prevent flutter of steel panels at 50,000 feet altitude; the panels are assumed to be very wide in the direction normal to the air flow. The lower curve is for a panel that is unstressed by forces in its plane; the upper curve shows the higher thicknesses needed to prevent flutter of a pnael that has been buckled by compressive forces. In addition, it can be stated that a compressive force of a magnitude that is not sufficient to buckle the panel would still make the panel more susceptible to flutter that if it were entirely unstressed; thus, the critical thickness ratios for compressed but non-buckled panels may be expected to lie between the two curves shown.

The increased susceptibility to flutter of panels due to thermal stress may be explained in terms of a *local* reduction of the effective stiffness of the panel against lateral deflection when it is subjected to compressive stresses in its plane. Once a panel has been buckled, whether by thermal stress or by applied loads (or by a combination of the two) there results in addition an *over-all* reduction of stiffness of the wing as a whole. Such over-all reductions of stiffness are due to the fact that the centre portions of buckled panels do not carry their full share of externally applied loads, and this kind of action has long been familiar to designers dealing with ordinary static analysis of wings with buckled skin elements. But, as we shall discuss next, losses of over-all stiffness can be caused by thermal stress *without* the occurrence of local buckling.

Reduced over-all stiffness resulting from chordwise temperature gradients. — Such over-all stiffness losses are produced in thin wings by certain variations of load along the chord that occur as a result of transient heating conditions. Figure 4 illustrates such a thermal loading for the case of a solid wing of diamond cross section. If we assume, for simplicity, that the coefficient of heat transfer from the boundary layer to the wing is constant along the chord, that the temperature is constant through the thicknesses, and that heat conduction along the chord may be neglected, then the distribution of temperature along the chord would be as shown by the top chart at some instant during the transient heating stage. Such a temperature distribution is a consequence of the fact that it naturally takes longer for the massive center of the chord to heat up than the relatively thin leading and trailing edges. Then, because the hotter portions of the cross section wish to expand in the spanwise direction but are constrained from doing so by the cooler midchord region, compressive stresses are produced near the leading and trailing edges while tension arises around the midchord. The thermally induced spanwise load per unit chord then varies along the chord in the fashion shown by the lower diagram. The resultant load on the cross section must, of course, vanish; but this kind of load distribution — compression near the ends of the cross section and tension around the middle — affects the over-all wing torsional stiffness in the manner illustrated by the conceptual model shown in Figure 5.

A rigid cross-bar is attached to one end of a torque tube that is fixed at the other end. In addition the cross-bar is joined to the foundation by means of a hinged bar attached at each end. Let us assume now that the end rods get hot while the torque tube remains relatively cool; then, because of the constraining action of the rigid cross-bar, compressive forces develop in the rods while a tensile force, numerically equal to the sum of these compressive forces, is produced in the tube. If we now subject the torque tube to an externally applied torque as shown by the arrow, the cross-bar rotates as indicated. But we note now that the end rods are inclined to their original positions, and remembering that they contain compressive forces, we see that components of each of these forces act to produce a couple on the cross-bar. Consequently, the torque tube is subjected to not only the externally applied torque but in addition to an extra torque arising from the compressive stresses in the end rods. As a result the twist of this idealized wing model is larger than it would be if compressive stresses in the rods had been absent. In other words, because of the thermal compressive stresses at the ends of the cross section the effective torsional stiffness of the structure has been lowered. In an entirely analogous fashion, the solid wing previously discussed, loaded longitudinally by thermally induced compressive forces near the leading and trailing edges, would lose some of its torsional stiffness.

Examination of this problem as it applied to several types of construction, including hollow wings and wings with multiple webs, indicates that the behavior described for the solid wing is true in general. Furthermore, the effect of chordwise variation in the heat transfer coefficient can be shown qualitatively to aggravate the situation.

The quantitative magnitude of the loss of torsional stiffness can be calculated, and Figure 6 shows some results for each of the three types of wing cross-section. Each wing is assumed to be made of steel, is supposed to have a thickness to chord ratio of 3 per cent, and is imagined to undergo, at an altitude of 50,000 feet, the idealized flight history shown in the upper sketch. That is, the wing is cruising at Mach number .75 and at time zero is instantaneously accelerated to Mach Number 3; the abscissa is a parameter proportional to time. The thermal stresses in the hollow wing are due only to the chordwise variation of the coefficient of heat transfer from a turbulent boundary layer; for the multiweb and solid wings, this variation is neglected, as before, and the heat transfer coefficient at the midchord due to a turbulent boundary layer is arbitrarily assumed to apply all along the chord. The lower chart shows the losses of torsional stiffness calculated on the basis of the various simplifying assumptions made for each wing. The ordinate is the effective torsional stiffness, GJ_{eff}, divided by the original GJ, and the abscissa is, again, proportional to time. It is seen that while the hollow wing experiences only a moderate loss of torsional stiffness (as a result of the chordwise variation of heat transfer coefficient) just the chordwise mass variation of the solid wing leads to a loss of 75 per cent of its original torsional stiffness. The calculations for the multiweb wing, made on the basis of a web-to-cover area ratio of .35, also show a substantial loss of stiffness. The maximum effects in the multiweb wing have not been calculated since the idealized assumptions made — namely, one temperature in the covers and another in the webs — are useful only near the beginning of the transient conditions. The curve for the multiweb wing would actually reach a minimum as did the others. After a long enough time, when all transients have disappeared and the wings are at a uniform temperature, their torsional stiffnesses would regain their original values (ignoring the reduction of the shear modulus G due to elevated temperatures).

The idealized flight history shown in Figure 6 is admittedly unrealistic and was chosen for convenience. However, similar calculations have been made for the case of the solid wing with the more realistic flight histories shown in Figure 7. To make the example more specific the solid wing has been assumed to have a chord of 36 inches and the variation with time in minutes of GJ_{eff}/GJ has been calculated for the three flight histories shown: infinite acceleration from Mach .75 to Mach 3, an acceleration of approximately 1 g up to Mach 3, and an acceleration of approximately $\frac{1}{2}$ g. As can be seen from the results, the maximum losses of stiffness during each of these flights occur at different times, but their magnitudes are very nearly the same. Consequently one may have a certain degree of confidence in the general magnitude of the stiffness effects calculated on the basis of an idealized flight history consisting of the instantaneous change from one Mach number to another.

Some Effects of Aerodynamic Heating on Aileron-Reversal and Flutter

Let us now consider the effect of such losses of torsional stiffness on a particular aeroelastic problem, the aileron effectiveness of such a wing of solid cross-section (Figure 8). We assume here that the wing has a rectangular plan form of aspect ratio 3 and is provided with a full span aileron whose width is 20 per cent of the chord. If the wing undergoes the flight history designated by the curve "A"— that is, a sudden change from Mach .75 to Mach 3 — the resultant history of rolling effectiveness is that shown by the curve labelled "A" in the lower chart. The ordinate is the rolling rate per unit aileron deflection divided by the same quantity for a rigid wing. The results show that about two minutes after the sudden attainment of Mach 3 more than half of the rolling effectiveness of the aileron would be lost. Eventually, when steady state temperatures are achieved, the effectiveness would return to the value it had at Mach 3 before the onset of thermal stresses. If, as shown by case "B," the wing were accelerated to Mach 3.5, all of the aileron effectiveness would be lost in less than a minute; in other words, the aircraft would suffer aileron reversal. The controls would remain reversed for 2-1/2 minutes, after which time effectiveness would gradually return.

A final example, illustrative of the aeroelastic effects of loss of torsional stiffness, may be of interest. We note first in Figure 9 the losses of torsional stiffness which would be experienced by a steel multiweb wing having many closely spaced webs with a ratio of web area to cover area of .35 and a skin thickness of 1/10 of an inch. The lower part of the slide shows the stiffness losses endured by the wing when it is subjected to the flight histories "A" and "B" shown above — instantaneous acceleration from Mach .75 to Mach 3 and 4 respectively. The substantial losses experienced soon after acceleration to Mach 4 can lead to the consequences shown in Figure 10. If we consider the wing to have a rectangular plan form with an aspect ratio of 3 and take into account the losses of torsional stiffness incurred by acceleration to Mach 4, a theoretical analysis of bending-torsion flutter yields the time variation of flutter speed given by the descending curve. The intersection of this curve with the flight history indicates that after 35 seconds of undisturbed flight at Mach 4, the wing would suddenly begin to flutter.

It should be emphasized that the bending-torsion flutter considered in the last example is a far cry from the flag waving type of flutter illustrated by the motion pictures referred to at the beginning of this paper; nevertheless, the prediction of temporary quiescence at a given Mach number followed by the sudden inception of flutter is strikingly similar to the behavior exhibited in the test.

Conclusion

In conclusion, it appears that the design of aircraft to withstand aeroelastic difficulties at high supersonic speeds will of necessity require the consideration of the effect of aerodynamic heating. Among the various aeroelastic consequences of aerodynamic heating, the reduction of over-all stiffness through the action of thermal stress is the most novel and may well turn out to be the most serious. An appreciation of this phenomenon must become part of the working equipment of the modern aeroelastician.

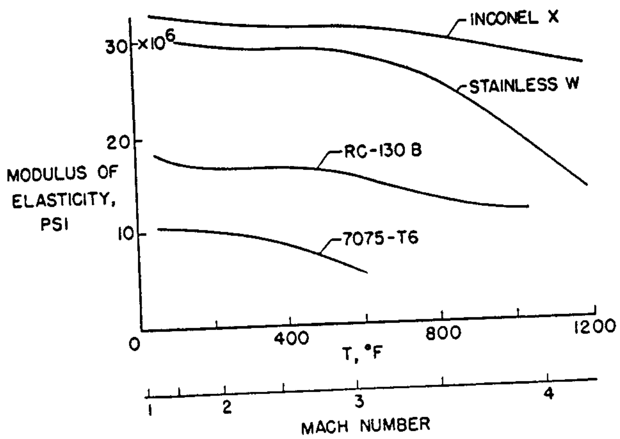

Fig. 1. Effect of temperature on the elastic moduli of several alloys.

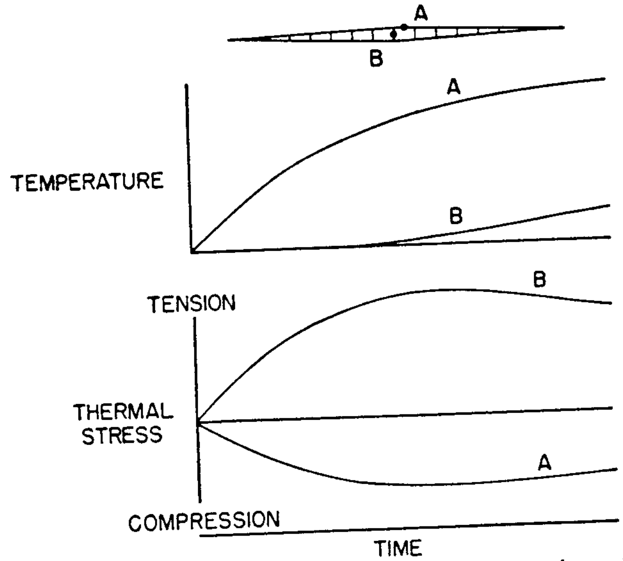

Fig. 2. Example of thermal stress resulting from accelerated flight.

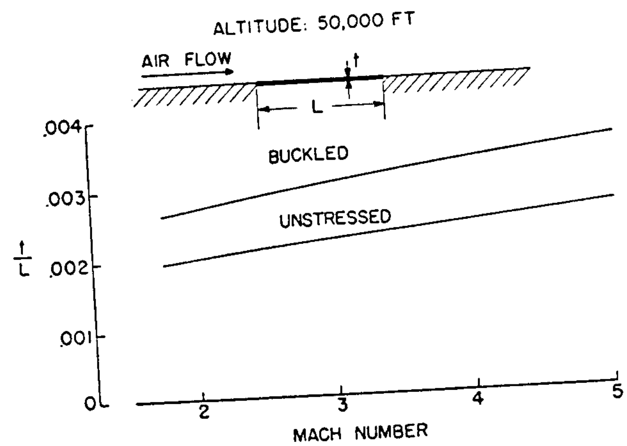

Fig. 3. Effect of heat-induced buckling and skin thickness on flutter of steel skin panels.

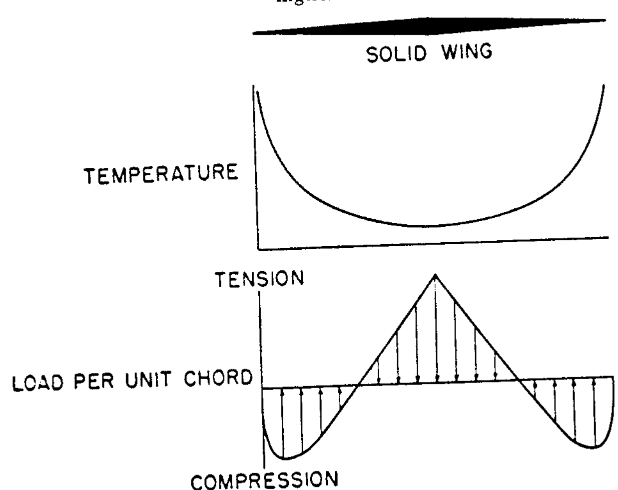

Fig. 4. An example of chordwise variation of thermal load.

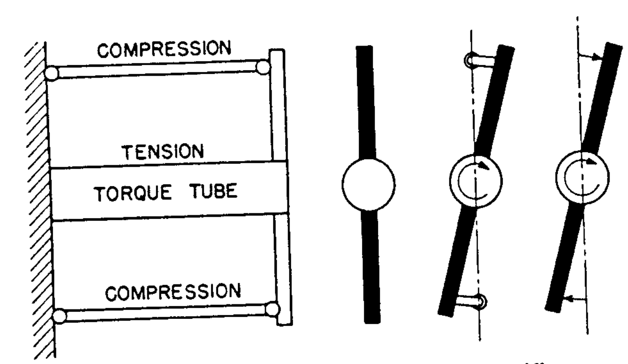

Fig. 5. Effect of thermal load on torsional stiffness.

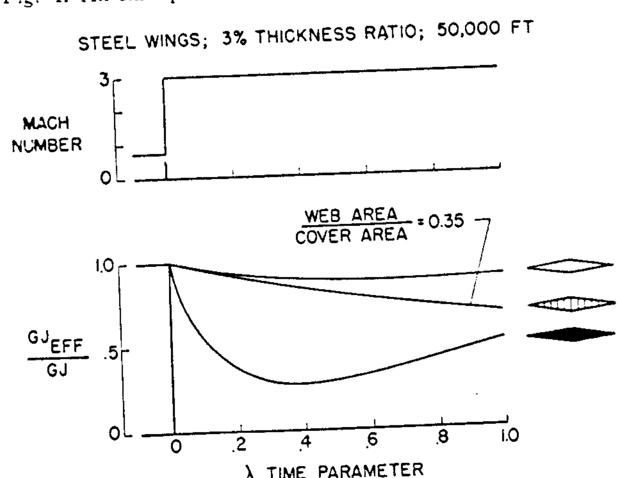

Fig. 6. Variation of torsional stiffness with time for three airfoil structures after instantaneous acceleration to Mach 3.

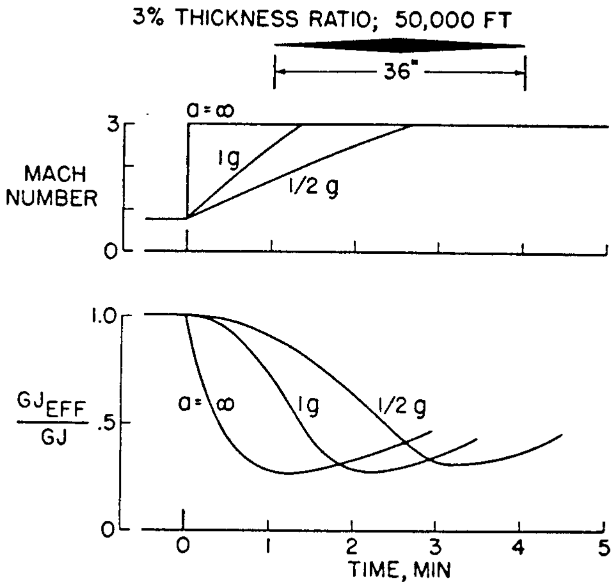

Fig. 7. Variation of torsional stiffness with time for a solid steel airfoil accelerated at various rates to Mach 3.

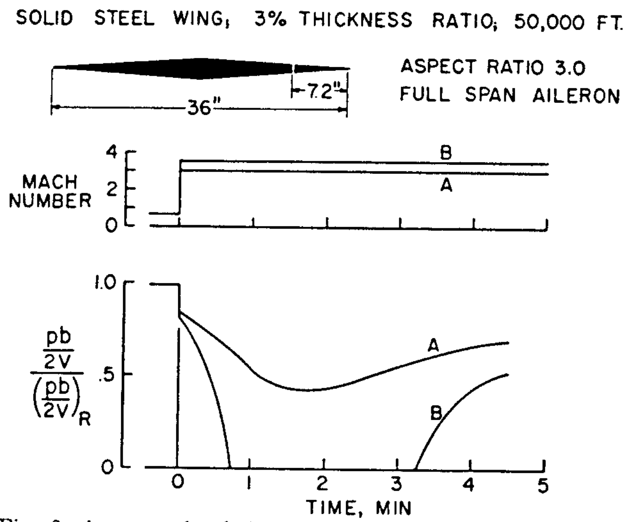

Fig. 8. An example of the effect of aerodynamic heating on rolling effectiveness.

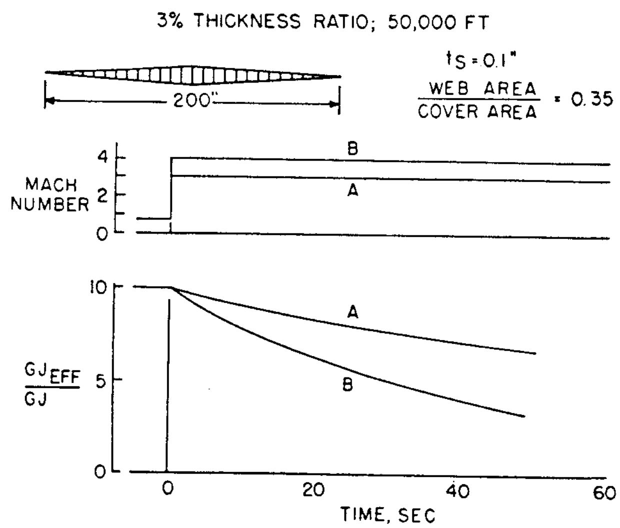

Fig. 9. Effect of Mach number and time on the torsional stiffness of a steel multiweb wing.

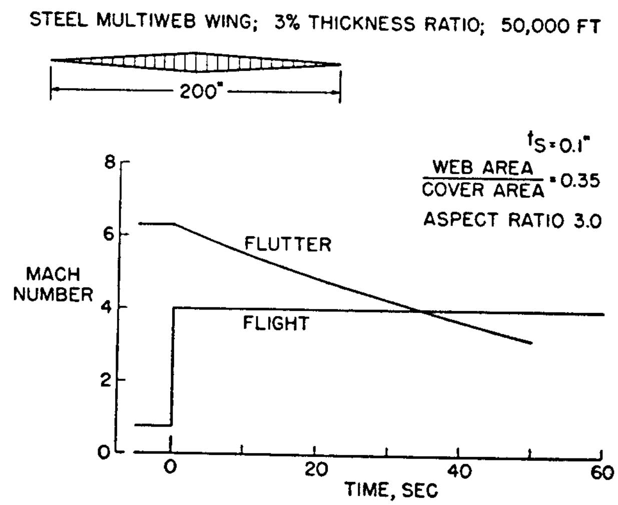

Fig. 10. An example of the effect of aerodynamic heating on wing flutter.

GENERAL DISCUSSION

Sir Arnold

Are there any comments?

Monsieur Roy

Je voudrais seulement exprimer mon admiration pour la clarté avec laquelle Mr. Dryden a mis en lumière et pas seulement sur l'écran quelques-unes des conséquences inattendues de l'échauffement aérodynamique de l'avion, et, pour le dire en un mot, j'ai l'impression que Mr. Dryden nous a fait, dans cette réunion de l'AGARD, assister à la naissance de ce qu'on appelera peut-être L'aéro-thermo-élasticité.

Sir Arnold

Are there any other comments?

Mr. Nicholson (UK)

In the discussion on aerodynamic heating various speakers have used various heights in their examples, but perhaps the effects of the choice of altitude on the severity of the problem have not really been sufficiently emphasised. If we confine our interest for the moment to the case of sustained level flight we can show that increase in altitude substantially reduces aerodynamic heating problems. The argument in this case is based on the fact that for a given Mach number and surface temperature the rate of aerodynamic heating is closely related to the work done in driving the aircraft through the air. Now, for an aircraft of given lift/drag ratio, speed and weight, the work done is the same irrespective of the design height. As the design height goes up, the surface area of the aircraft goes up to get the lift equal to the weight but the total drag and hence the total heating remain the same. Now, the losses by radiation will go up in proportion to the surface area and hence the final equilibrium temperature which is achieved will be lower the greater the design height. I should emphasize that this argument refers to sustained level flight and does not apply to certain other cases of high altitude flight at very high Mach numbers. The point I would like to make, and to submit for comment is that the choice of high altitude when designing for high Mach number steady flight does give a very real relief to the rate at which this aero-dynamic heating problem and the general structural problems which go with it, increase as Mach number increases. Thus, although the problem is of course formidable, it may not, when we take the choice of height into account, be as formidable in the use of steady long range airborne aircraft as is sometimes thought.

Sir Arnold Hall

Thank you very much, Mr. Nicholson. I would like to endorse what has been said, that altitude has an influence on these matters. Perhaps you would like to comment on this point, Dr. Dryden.

Dr. Dryden

I think that it might be well to state what I think is the implicit assumption in Mr. Nicholson's remarks. I think the assumption is that you are dealing with turbo-jet-powered airplanes which land in the normal fashion. Of course, as a first approximation both the thrust and the drag would decrease in the same manner with an increase in altitude or decrease in density and the speed should be independent of altitude. However, since the air gets colder as we go higher we can put a little more fuel into the engines before we reach the temperature limit of the turbine blades so that airplanes as we know them travel at their greatest speed at an altitude of 35 or 40,000 feet. Now, if you abandon the landing requirement and talk about what may be obtained in rocket-powered airplanes in which the thrust is independent of the altitude, then of course the whole matter changes very drastically. In particular if you think of using a boost rocket to get to a very high altitude, there is the problem of coming down again, and the situation changes once more. I think that if we say that we are thinking only of the design of piloted turbojet airplanes, I agree fully with Mr. Nicholson's remarks.

Dr. von Karman

I would like to ask Dr. Dryden one question. If you consider the thermoelastic problem there are several degrees of approximation possible. In first approximation the heating is determined by the flow problem which refers to the undeformed structure. In other words one solves the flow problem around the undeformed structure and determines the heat transfer caused by the flow. In a higher approximation one has to take into account the deformation produced by heating influencing the flow and therefore also the heat transfer. If we take into account this effect we have a real mutual interaction between heating and deformation similar to the interaction between flow and deformation characteristic for aeroelastic problems.

This interaction probably presents beautiful new mathematical problems. I may ask Dr. Dryden, what has been done in this direction?

Dr. Dryden

Very little has been done. If you recall I discussed only the very simple first order effect, the effect of the heating on the structural stiffness, ignoring for the time being all these other factors you mention. Although it does not answer your question directly, I think it might help to give a little bit of the background. We have been considering this matter of simulation of aerodynamic heating effects on structures for quite some time. At first we decided to simulate the thermal history in the manner described by Dr. Walker with radiant heating, but not to simulate the airflow. There was some small airflow past the structure but we were not attempting to simulate the magnitude of the airflow. Now we knew it would take two more years to build a facility to do what we wished to do. In the meantime we decided that we could not sit around and wait but that we should make a beginning. The beginning was the very modest one of starting to make a few measurements in a supersonic airstream. You saw in the film the unexpected results. We then decided that while this simple case was possibly subject to analysis, if we really get the interaction that Dr. von Karman describes, it might be some time before the theory would be in a position to handle all of the complex interactions. And so we have changed the design of the structural facility and to the amusement of many structural engineers, the structural facility turns out to be a wind tunnel, a blow-down wind tunnel in which both the Mach number and the thermal history can be simulated. It will be some years before we have this facility but since the theory is in such a pioneering state we decided that we had better play safe on the facility by providing for the simulation of both the speed and the thermal history.

Dr. von Karman

Well, I must say that I am very glad that the structural engineer uses the wind tunnel as a structural experimental facility. About fifteen years ago I had some experience with structural engineers when a bridge in the United States collapsed because of aeroelastic effects. In the first meeting on the subject one of the most eminent structural engineers in the United States asked me: "But, you don't mean seriously that when in the future we design a suspension bridge then we have to put a model in a wind tunnel?" "This is exactly what I believe" was my answer.

Sir Arnold Hall

Dr. Walker, have you any comments on this point?

Dr. P. B. Walker

I have actually no questions to ask Dr. Dryden, but I might comment on one or two matters that have interested me particularly. The effect of mere loss of stiffness, as I think Dr. Dryden has suggested, can be dealt with by orthodox techniques of flutter analysis. The existence of what are virtually built-in stresses arising from the thermal condition is a rather more disturbing feature. I have regarded the effect as one in which the actual frequency of the system is changed artificially. I hope, however, that before we need and before we can attain a complete understanding of this phenomena — I hope I am not misinterpreting Dr. Dryden when I take it as agreed there is still quite a lot of investigation to be done — structural engineers can to some extent anticipate the phenomena in a general way by providing more stiffness and in particular by building-in more rigidity to resist buckling. May I also comment on a remark of Dr. von Karman. Speaking not particularly for myself but for structural engineers as I know them, I think they will certainly do their best to avoid having to use a wind tunnel.

Mr. Hartshorn

I should like to ask a very simple question. Metallurgical engineers are obviously going to be roped into this to help solve the problems and one question which has been asked to me by several people, is: If the characteristics of structural materials have got to suffer, which characteristic is the most important to keep? Is it stiffness or strength, or which is the one that you would prefer not to be interfered with?

Mr. Walker

The answer to that is. . . . . quite frankly. . . . I don't think we can make sacrifices of any of these features.

Sir Arnold Hall

Is there any other comment?

Dr. Mullins

Mr. Chairman, I should like to refer briefly to Professor Broeze's paper. Unfortunately he is not here, so I will limit my remarks to a certain extent. I have, however, had the benefit of a preliminary discussion of his paper with him on Wednesday evening. I think the paper is very provocative, probably deliberately so.

When Prof. Broeze computed the combustion intensity for the piston engine by taking a small part of the total crank angle as the effective combustion time, he was of course perfectly correct insofar as an absolute consideration of the combustion zone and burning rate in that zone was concerned. But when he goes on to compare these intensity figures with intensity figures for the gas turbine, in which the time of burning includes the time of evaporation and mixing of the fuel, the comparison breaks down. For the effective time in the homogeneous flame zone of the gas turbine may represent a few per cent only of the total combustion chamber transit time, and this means that the intensity of gas turbine combustion obtained by using an over-all transit time is down by an order at least and possibly nearly two orders.

When Prof. Broeze was speaking about the effect of fuel: air ratio he did not make a reference to the fact that the mixture gradients have a strong influence. When the fuel: air mixture is heterogeneous the prime influence of mixture strength is exerted through the temperature of the mixture of the products of combustion of one zone with an adjacent unburned zone containing reactants only. It can be shown that there is an optimum combustion intensity as the reaction temperature is increased due to the counterposing influences of decreasing reactant concentration and increasing chemical reaction rate. I think Prof. Broeze's paper merits further close attention.

Sir Arnold Hall

As there seems to be no other comments, the meeting is adjourned.